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Multiple Parton-Parton Interactions and the Effects of Varying Impact Parameters[1]

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ABSTRACT

The possibility of having several independent parton-parton interactions in a hadron-hadron collision is studied. A simple framework is developed for the effects of varying impact parameters. Properties studied include multiplicity distributions, forward-backward correlations, minijet rates and average transverse momentum dependence on multiplicity.

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In this talk I wish to discuss the phenomenological consequences of having several parton-parton interactions in a given hadron-hadron collision. The basic model is presented in [1], with further studies being carried out in collaboration with Maria van Zijl.

A detailed description of hard collision events must involve a number of components, such as the hard parton-parton interactions with cross-sections given by perturbative QCD, initial and final state parton showers, structure functions and jet fragmentation. Because of the ensuing complexity, a Monte Carlo approach has been adopted. For the results presented here we have used the Lund Monte Carlo, PYTHIA version 4.6[2] and JETSET version 6.2[3].

The differential cross-section for a hard parton-parton interaction is given by perturbative QCD, as a convolution of the hard scattering matrix elements and the structure functions of the incoming hadrons. The integrated cross-section of all interactions with $p_\perp > p_{\perp min}$, $\sigma_{hard}(p_{\perp min})$, is divergent for $p_{\perp min} \to 0$. At present collider energies, $\sigma_{hard}(p_{\perp min})$ becomes comparable with the total cross-section for $p_{\perp min} \approx 1.5$ GeV. This need not lead to contradictions: $\sigma_{hard}(p_{\perp min})$ does not give the hadron-hadron cross-section but the parton-parton one. Each of the two incoming hadrons may be viewed as a beam of partons, with the possibility of several parton-parton interactions when the hadrons pass through each other, so that $\sigma_{hard} > \sigma_{tot}$ is perfectly allowed.

In [1] we argue that collider data indicate a significant probability for multiple interactions at 540 GeV. This conclusion is based on the assumption of jet universality, i.e. that the underlying fragmentation mechanism in hadron physics is no different from that in e^+e^- annihilation. In the latter process, the Lund string fragmentation model[4] provides an accurate description of most phenomenology known to date. The way strings will be stretched in hadron physics is more complicated than in e^+e^- annihilation, however. Our standard assumption is that in low-$p_\perp$ events there are two strings being stretched, *e.g.* for $p\bar{p}$ collisions one between a quark in the p and an antiquark in the $\bar{p}$ and one between the remaining diquark and antidiquark. In high-$p_\perp$ events the strings are stretched out to the two scattered partons[2], in such a way that the simple two-string picture is recovered when the $p_\perp$ of the hard interaction is allowed to vanish (at least for the dominant one-gluon-exchange graphs). Within the framework outlined above, the predicted multiplicity distribution is much narrower that the experimental one, and forward-backward multiplicity correlations are almost absent.

If different parton interactions above $p_{\perp min}$ are assumed to take place (essentially) independently of each other, one obtains a Poissonian multiplicity distribution in the number of interactions, with mean given by $\sigma_{hard}(p_{\perp min})/\sigma_{tot}$, where σ_{tot} is the total inelastic, nondiffractive cross-section. With a varying number of interactions, the multiplicity fluctuations are increased, and strong forward-backward multiplicy correlations are introduced. Results are sensitive to the choice of $p_{\perp min}$ value, see Fig. 1, with a reasonable description obtained for $p_{\perp min} = 1.6$ GeV. Forward-backward multiplicity correlations, the rate of "hot spots" and other phenomena are also well described with this choice.

The relative lack of low-multiplicity events in the model may look like more of a problem than probably it is: our multiple interaction model is not intended to cover any kind of diffractive events. Whereas single diffractive events only rarely fulfill the experimental triggering conditions, most double diffractive do. Using the simple diffractive model recently implemented in PYTHIA[2], one can obtain a fair description also for the low-multiplicity tails. Unfortunately, the double diffractive cross-section is very poorly known, so it is difficult to know how much faith to put into a chance agreement before more detailed studies have been performed.

We have so far assumed that the initial state of all hadron collisions is the same, whereas in fact each collision is also characterized by a varying impact parameter b (b is in this paper to be thought of as a distance of closest approach, not as the Fourier transform of the momentum transfer). A small b value corresponds to a large overlap between the two colliding hadrons, and hence an enhanced probability for multiple interactions. A large b, on the other hand, corresponds to a grazing collision, with a large probability that no parton interactions at all take place. This effect will tend to broaden the minimum bias multiplicity distribution at higher energies. At present energies it does not make much of a difference, since the mean number of interactions is small anyhow. It may explain the "pedestal effect", however: events containing hard interactions are biased towards small impact parameters, and hence have a larger than average multiple interaction probability.

In order to quantify this, one may assume a spherically symmetric distribution of matter inside a hadron, $P(\bar{x})d^3x$. For simplicity, the same spatial distriscale change in t one obtains

$$\begin{aligned}\tilde{O}(b) &\propto \int\int d^3x dt\, P(x-\frac{b}{2},y,z-\frac{t}{2})P(x+\frac{b}{2},y,z+\frac{t}{2}) \\ &= \int dt \int d^3x\, P(x,y,z)P(x,y,z-(b^2+t^2)^{1/2}) \qquad (2)\end{aligned}$$

The average number of interactions is now assumed to be proportional to this overlap

$$< n_{int}(b) >= k \cdot \tilde{O}(b) \qquad (3)$$

where the constant of proportionality is related to the integrated parton-parton cross-section, and hence increasing with the CM energy. For a given impact parameter, the number of interactions is assumed to be distributed according to a Poissonian. In order to obtain finite cross-sections for the Gaussian and exponential matter distributions, one has to assume that each event contains at least one semihard interaction. The probability that two hadrons, passing each other by with an impact parameter b, will actually interact is then given by

$$P_{int}(b) = 1 - exp(-k\tilde{O}(b)) \qquad (4)$$

Although not made use of explicitly here, this approach leads to an increasing total cross-section with energy and a "blackening" of the incoming hadrons for any given impact parameter[6].

The presence of some regularization of the divergent parton-parton cross-section can be motivated by the fact that the incoming hadrons are colour singlets: a gluon of small $p_\perp$, and hence large transverse wavelength, will not resolve the individual colour charges inside the hadrons and therefore effectively decouple. For the study of varying impact parameters it makes sense to use a more continuous regularization than the sharp cutoff at $p_{\perp min}$, and to extend the generation of semihard interactions to $p_\perp = 0$, so that the requirement of at least one semihard interaction sometimes corresponds to a very soft interaction. The matrix elements, which normally diverge like $dp_\perp^2/p_\perp^4$ are therefore multiplied by a factor $p_\perp^4/(p_{\perp 0} + p_\perp^2)^2$. Further, α_s is evaluated at a scale $p_{\perp 0}^2 + p_\perp^2$ rather than at $p_\perp^2$. With $p_{\perp 0} \approx 1.8$ GeV we reproduce the same phenomenology at 540 GeV as above with a sharp cutoff at $p_{\perp min} \approx$ 1.6 GeV. Given the ratio of the (regularized) integrated parton-parton cross-section and the total (inelastic, nondiffractive)cross-section, the k value can be determined.

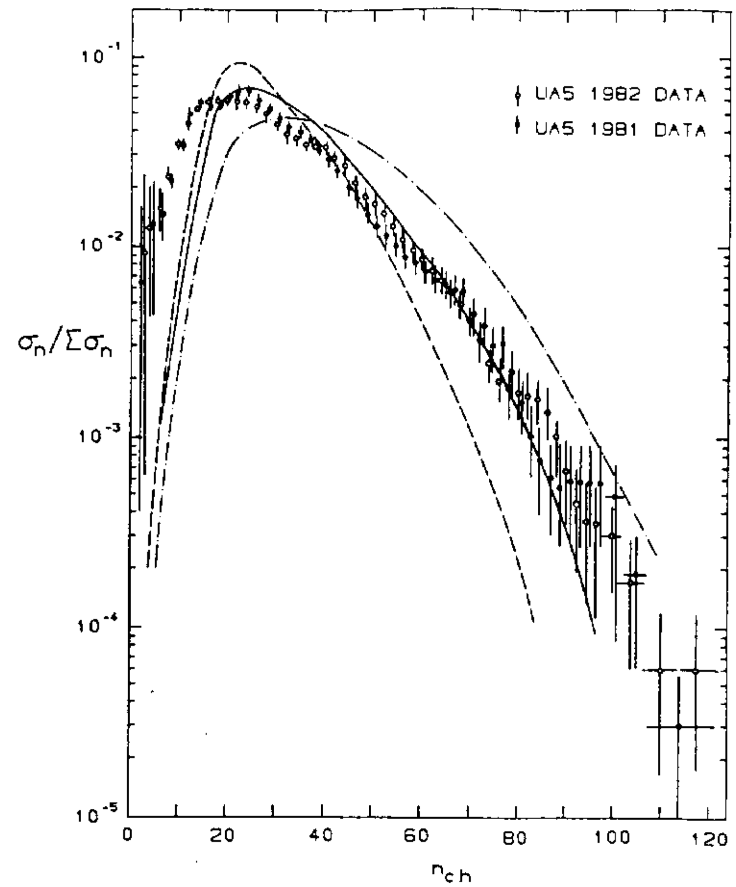

Figure 1: Charged multiplicity distribution at 540 GeV, UA5 results[5] compared with multiple interaction model: dashed $p_{\perp min}$ = 2.0 GeV, full 1.6 GeV and dash-dotted 1.2 GeV.

bution is taken to apply for partons of all species and momenta. Three different parametrizations will be compared, a solid sphere $P(\bar{x}) \propto \Theta(a - |\bar{x}|)$, a Gaussian $P(\bar{x}) \propto exp(-x^2/a^2)$ and an exponential $P(\bar{x}) \propto exp(-|\bar{x}|/a)$, to check how sensitive results are to this choice. During the course of a collision with impact parameter b, the integrated overlap between the colliding hadrons is then given by

$$\tilde{O}(b) = \int\int d^3x dt\; P_{boosted}(x - \frac{b}{2}, y, z - vt) P_{boosted}(x + \frac{b}{2}, y, z + vt) \qquad (1)$$

where v is the velocity in the CM frame and $P_{boosted}$ the suitably Lorentz contracted $P(\bar{x})$. By a scale change in z, $P_{boosted}$ can be replaced by P, however. After a further

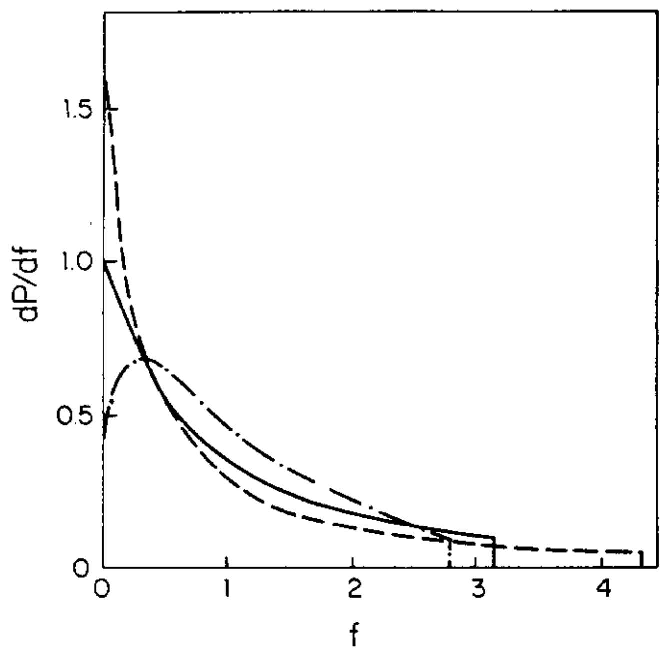

Figure 2: Distribution of events in relative multiple interaction probability f, dash-dotted solid sphere, full Gaussian, dashed exponential.

Using the equations above, the probability distribution in b of events may be obtained, and for each b the average number of interactions to be expected. For practical applications, it is more useful to define a factor $f(b) = \tilde{O}(b)/ < \tilde{O} >$, and study the probability distribution dP/df. This is shown in Fig. 2 for the three hadronic matter distributions above at 40 TeV. A large f value corresponds to a central collision, with high probability of several interactions, while a small f corresponds to a peripheral collision with the minimal number of one interaction. The larger a tail the hadronic matter distribution has, the wider is the dP/df distribution.

The resulting scaled multiplicity distributions at 40 TeV are shown in Fig. 3, for comparison also without any impact parameter dependence ($f = 1$ always). We see that results in the tail do depend on the shape of the hadron matter distribution, but with the more realistic Gaussian and exponential distributions the outcome is not that much different. For comparison, the tail of the experimental data at 540 GeV

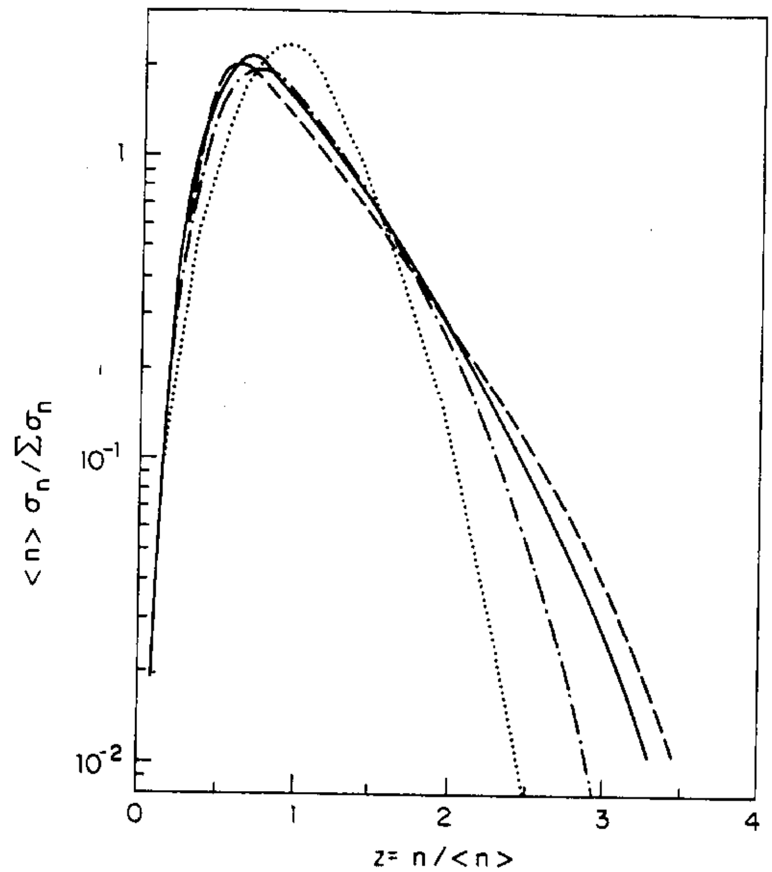

Figure 3: Scaled charged multiplicity distribution at 40 TeV, dash-dotted for solid sphere, full Gaussian, dashed exponential, dotted fixed impact parameter.

is only slightly below our Gaussian curve at 40 TeV; the data is broadened by double diffraction, however.

When the evolution of the scaled multiplicity distribution is studied as a function of CM energy, the scenario that emerges is the following. Up to ISR energies, the width is determined mostly by fragmentation effects and by how the two strings of low$-p_\perp$ events share the total energy. The basic fragmentation mechanism is Poissonian in nature, however, and would lead to a narrowing scaled multiplicity at $Sp\bar{p}S$ energies. Here the importance of hard interactions begins to be felt, but having at most one hard interaction only slows down the narrowing trend. It is the effects of a varying number of parton-parton interactions that makes the scaled

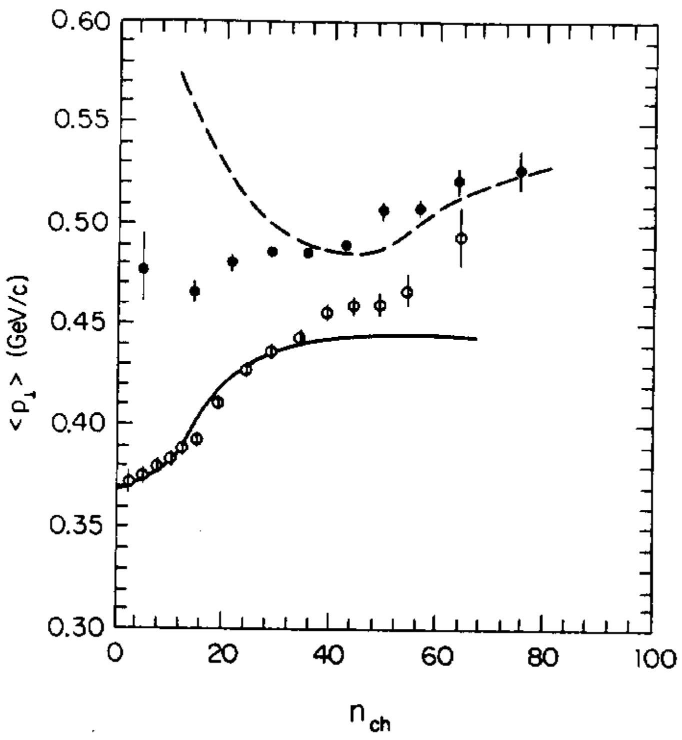

Figure 4: Mean charged particle transverse momentum as a function of charged multiplicity, open and full circles UA1 data[7] for nojet and jet events, full and dashed curves the same for the model.

multiplicity distribution broaden in this energy range. Not taking into account the variation in impact parameters, the number of interactions is again given by an essentially Poissonian distribution at SSC energies. It is only the effects of varying impact parameters that leads to a non-Poissonian distribution in number of hard interactions at very high energies, and thus a non-shrinking scaled multiplicity distribution. It is not all that much broader than at present energies, however. Finally, one also has to remember that double diffractive events have a lower average multiplicity, thus broadening the overall multiplicity distribution.

The $UA1$ minijet analysis [7] provides us with a number of other event characteristics that it may be interesting to compare with. We have tried to reproduce the given minijet selection criteria, requiring a $\Sigma E_\perp > 5$ GeV within a cone $\Delta R = ((\Delta\eta)^2 + (\Delta\phi)^2)^{1/2} < 1$ around the jet direction, with this direction restricted to certain regions in pseudorapidity η and angle ϕ. At 200(900) GeV, the fraction of events containing a minijet is 5.9% (17.2%) in the $UA1$ data and 2.3%(11.6%) in our model. Now, the effects of calorimetric fluctuations are important and, introducing a Gaussian smearing (cut off at 0 and $2E_\perp$) with $\sigma = 0.6\sqrt{E_\perp}$ for the neutral energy cell-by-cell in the Monte Carlo analysis, the minijet rate is increased to 5.1% (18.5%), in good agreement with data (if the smearing is done for the total charged and neutral energy, the results instead become 6.6%(21.2%)). For the jet and nojet samples separately, we obtain a fair description of the mean charged multiplicity and the width of the multiplicity distribution, in particular that the distribution is much narrower in the jet than in the nojet case, and that approximate KNO scaling is observed for the jet and nojet samples individually.

Most interesting is maybe the dependence of the mean charged particle transverse momentum $< p_\perp >$ on the charged multiplicity n_{ch}, Fig. 4. Since the events at low multiplicity are predominantly of the nojet kind and those at high multiplicity of the jet kind, it is seen that the description of the sample as a whole is very good. In particular, it should be noted that no parameters have been tuned to obtain the right $< p_\perp >$ value, rather this is unambiguously given by the perturbative QCD matrix elements and by the fragmentation model constrained to fit e^+e^- data. There is a very glaring discrepancy in the low-multiplicity region for the minijet events, however. In the model, the $< p_\perp >$ goes up when n_{ch} becomes very small, since the minimum $\Sigma E_\perp$ of 5 GeV gets to be shared between fewer and fewer particles. An increasing fraction of the $\Sigma E_\perp$ is obviously contributed by neutral particles but not enough in our model. It is yet too early to say whether the discrepancy would be removed with a better understanding of detector smearing effects, in particular for the possibility of occasionally reconstructing a much larger $E_\perp$ in a cell than really was deposited there (this could be studied by observing how well the $p_\perp$ is balanced), or whether it represents a piece of physics not yet understood.

In summary, there can be no doubt that the mechanism of multiple parton-parton interactions must be present at some level. We have taken the attitude that it is meaningful to use perturbation theory down to transverse momenta in the order of 1.5 GeV, in which case multiple interactions becomes an important factor in the understanding of the beam jet structure. Such an approach passes the test of providing a fair description of existing data, and is yet predictive enough that it can be proven wrong.

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References

[1] T. Sjöstrand, Fermilab-Pub-85/119-T

[2] H.-U. Bengtsson, Computer Phys. Comm. **31**, 323(1984)
H.-U. Bengtsson, G. Ingelman, Computer Phys. Comm **34**, 251 (1985)
H.-U. Bengtsson, T. Sjöstrand, in preparation.

[3] T. Sjöstrand, Computer Phys. Comm **39**, 347 (1986)

[4] B. Andersson, G. Gustafson, G. Ingelman, T. Sjöstrand, Phys. Rep. **97**, 33 (1983).

[5] UA5 Collaboration, G. J. Alner et al., Phys. Lett. **138B**, 304 (1984).

[6] Cf. talks by L. Durand and B. Margolis in these proceedings.

[7] F. Ceradini (UA1 Collaboation), in Proc. of the International Europhysics Conf. on High Energy Physics, Eds. L. Nitti, G. Preparata (Laterza, Bari, 1985), p. 363.